

Spiral and Bar Instabilities Provoked by Dark Matter Satellites

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Abstract. We explore the secular dynamical evolution of an N-body model of M31 in the presence of a population of 100 dark matter satellites over 10 Gyr. The satellite population has structural and kinematic characteristics modelled to follow the predictions of Λ CDM cosmological simulations. Vertical disk heating is a small effect despite many interactions with the satellite population with only a 20% increase in vertical velocity dispersion σ_z and the disk scale height z_d at the equivalent solar radius $R = 2.5R_d$. However, the stellar disk is noticeably flared after 10 Gyr with z_d nearly doubling at the disk edge. Azimuthal disk heating is much larger with σ_R and σ_z both increasing by $1.7\times$. However, in a control experiment without satellites dispersion increases by $1.5\times$ suggesting that most of the effect is due to heating through scattering off of spiral structure excited by swing-amplified noise. Surprisingly, direct impacts of satellites on the disk can excite spiral structure with a significant amplitude and in some cases impacts close to the disk center also induce the bar instability. The large number of dark matter satellite impacts expected over a galaxy's lifetime may be a significant source of external perturbations for driving disk secular evolution.

1. Introduction

Cosmological simulations in Λ CDM show that the dark matter halos of galaxies contain hundreds to thousands of subhalos or dark satellites (Moore et al. 1999; Gao et al. 2004; Diemand et al. 2007). The existence of subhalos raises interesting questions about the dynamical evolution of disk galaxies. While this population is under-represented in the observed satellites (Klypin et al. 1999), the recent success of Λ CDM in accounting for many properties of the universe from the CMB to the large-scale structure leads us to take this prediction seriously. Cosmological infall of a large number of dark satellites onto a typical spiral galaxy could be a major source of disk heating and thickening (Tóth & Ostriker 1992; Font et al. 2001; Benson et al. 2004; Kazantzidis et al. 2007) beyond known astrophysical processes so it is important to quantify the effect and see if the observed galaxy population is morphologically consistent. A main difficulty with numerical studies is that N-body disks are prone to self-heating

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by two-body relaxation with inadequate resolution so that any perturbations by satellites can easily be masked by numerical effects. Ad hoc assumptions about the structure of satellites also make the interpretation of results difficult in light of the predictions of Λ CDM.

In this study, we attempt to overcome these problems using new galaxy simulations with sufficient resolution to measure the heating directly due to a cosmologically inspired model population of dark matter satellites. These simulations reveal the importance of satellite impacts – i.e direct passage of satellites through the stellar disk – in exciting both spiral and bar instabilities. Dark satellite interactions may therefore be an essential driver of secular dynamical evolution of disk galaxies (see also Kazantzidis *et al.* (2007)).

2. Methods

For the study here, we use the stable, equilibrium axisymmetric model of M31 derived from a distribution function as described in Widrow & Dubinski (2005). We model M31 with an exponential disk, a Hernquist model bulge, and a cuspy dark halo with an NFW profile. Model parameters are determined that fit the rotation curve and surface brightness profile for M31 with an assumed M/L ratio for the stellar components such that the disk remains stable against bar formation for 10 Gyr.

The method for generating a satellite population is described in detail in Gauthier *et al.* (2006). The satellite properties reflect cosmological numerical predictions for the subhalo mass function, radial distribution, tidal radii as well as internal density structure. To summarize, 10% of the dark matter halo mass is initially in 100 subhalos spanning a mass range of $10^8 - 10^{10} M_\odot$ selected from a mass function $dN/dM \sim M^{-1.8}$. The radial number density of satellites are set according to the formulae presented in Gao *et al.* (2004). Our highest resolution galaxy model contains the following numbers of particles: 10M disk, 5M bulge, and 20M smooth halo for a total of 35M. The 100 dark satellites each contain 100K particles for a total of 10M. We run the simulation using a parallelized treecode (Dubinski 1996) with a fixed Plummer softening length $\epsilon = 15$ pc and 20000 equal timesteps with $\delta t = 0.49$ Myr. Total binding energy is conserved to within 0.3% and total angular momentum is conserved to within 2%. We also use models with 10 times fewer particles in some additional studies.

3. Disk Heating

We first ran a control simulation at 35M particles to understand numerical effects (Fig. 1). Vertical disk heating is negligible over most of the disk with almost no change in σ_z and the vertical scale height at this resolution. However, the radial and azimuthal velocity dispersions grow by 50% due to spiral instabilities arising from swing amplified Poisson noise in the disk particle distribution. We then added satellites in two different runs with statistically similar distributions. In our first simulation, the disk developed a bar half way through the run (Gauthier *et al.* 2006) and so introduces an unwanted additional source of heating (see Movie 1). The formation of a bar was unexpected and we will discuss the origin of this instability shortly. Fortunately in the second run, no bar formed

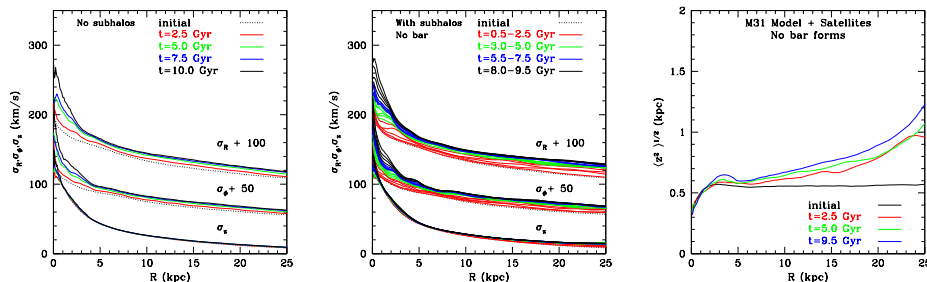


Figure 1. The evolution of the disk velocity ellipsoid for the control simulation (no subhalos) and the simulation with 100 dark satellites with no bar instability. Also, the evolution of the vertical scale-height as measured by the variance in z at different radii.

so we could directly measure heating effects by the satellite population (Fig. 1). Vertical heating is still small with roughly a 20% increase in σ_z even under the bombardment of satellites. The increase in σ_r and σ_θ is also only 20% over and above the heating caused by intrinsic spiral instabilities. However, there is a noticeable flaring of the disk in the presence of satellites with the scale height nearly doubling from 2 disk scale lengths to the disk edge. Kazantzidis et al. (2007) also see this effect in similar work. Similar features are seen in the outer disk of M31 (Ibata et al. 2007).

4. Spiral and Bar Instabilities from Satellite Impacts

An unexpected feature of these simulations is the induced bar instability in our first run as well as easily distinguished multi-armed global spiral structure. The main cause of these features are satellite impacts. The passage of a satellite through the disk induces a localized disturbance that presumably grows by Toomre’s swing amplification mechanism (Toomre 1981). Note that the tidal effects of the satellites are generally small and so this mechanism is quite different than the tidal interactions responsible for grand-design spiral galaxies like M51. The mechanism is closer to the original ideas suggested by both Goldreich & Lynden-Bell (1965) and Julian & Toomre (1966) where a mass perturbation appearing within the disk – a giant molecular cloud or massive star forming region – is the source of a disturbance that is subsequently amplified.

A virtual fly by of the evolving galaxy clearly shows episodes of spiral structure excitation immediately after satellites pass through the disk (see Movie 2). In the case of model with the bar instability, there appears to be a single strong encounter with one of the more massive satellites near the center of disk just before the onset of the bar. It seems likely the disturbance caused by the passing satellite disrupts the center of the galaxy enough to make it susceptible to the swing-amplifier feedback loop (Toomre 1981).

We are testing these ideas further with more experiments and idealized perturbations representing satellite passages through the disk. We performed 10 additional experiments with 4.5M particle models and statistically independent

but consistent satellite populations in orbit around M31 (see Movie 3). Five out of ten of these models develop a bar instability during their lifetime apparently due to chance central encounter with a massive satellite. Those models that do not suffer strong central encounters with satellites avoid bar formation. In all cases, spiral perturbations of significant amplitude are observed due to satellite interactions.

We are now doing a quantitative study of the effect of satellite impacts on disks using a transient mass perturbation appearing within the plane of the disk. Preliminary results suggest that even satellite masses as small as $10^9 M_\odot$ or roughly 5-10% the mass of the LMC are large enough to induce obvious spiral structure while the passage of a LMC-sized satellite creates a strong response (see Movie 4). A typical galaxy will experience dozens of impacts with satellites more massive than $10^9 M_\odot$ during its life according to the predictions of Λ CDM. Dark satellite impacts may then play an important role in maintaining the multi-armed, global spiral patterns seen in the disk galaxies. At this stage, we need to quantify the response of a disk as a function of satellite impactor mass and impact radius on the disk. The orbital statistics of Λ CDM subhalos from cosmological simulations will allow us to determine the frequency, mass distribution and distribution of impact radii expected on a galactic disk over its history. By combining these two results, we should be able to quantify the effect of dark satellites on disk secular evolution and so address observations of the morphological appearance of galaxies including the bar fraction (Jogee et al. 2004) throughout cosmic history.

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MOVIES 1,2,3 & 4 are available at:

<http://www.cita.utoronto.ca/~dubinski/Rome2007>

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